A new ductility index for railway prestressed concrete sleepers with holes and web openings considering fragility and failure criteria

Kaewunruen, Sakdirat; Gamage, Erosha Kahawatta; Minoura, Shintaro; Remennikov, Alex

A NEW DUCTILITY INDEX FOR RAILWAY PRESTRESSED CONCRETE SLEEPERS WITH HOLES AND WEB OPENINGS CONSIDERING FRAGILITY AND FAILURE CRITERIA

Sakdirat Kaewunruen[1,2], Erosha K Gamage[1], Shintaro Minoura[3] and Alex M Remennikov[4]

[1] *School of Engineering, The University of Birmingham, U.K.*

[2] *Birmingham Centre for Railway Research and Education, The University of Birmingham, U.K*

[3] *Railway Dynamics Division, Railway Technical Research Institute, Japan*

[4] *School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia*

ABSTRACT

Prestressed concrete sleepers (or railroad ties) are designed in order to transfer wheel loads from the rails to the ground of railway tracks and to secure rail gauge. Their design generally takes into account static and dynamic loading conditions. Some sleepers have been retrofitted on site to install accessory equipment such as signaling, fiber optic, equipment cables, etc. Without protection, the equipment will be damaged either by ballast corners or by tamping machine. Thus, concrete sleepers are often pre-drilled in order to create holes and web openings to cater cables internally so that they would not experience detrimental or harsh environments. Also, the retrofits on concrete sleepers for automatic train control device and similar signaling equipment often require holes and web openings. In contrast, the effects of holes and web openings on structural capacity of concrete crossties have not been thoroughly investigated. This paper thus highlights experimental methods to investigate the effect of holes and web openings on the fragility and failure of railway concrete sleepers. The insight into the fragility and failure modes has resulted in a proposal to develop a new ductility index that can better inform the structural capacity and health monitoring for retrofiting prestressed concrete crossties with holes and web opening, which is also suitable in practice.

Keywords: Concrete sleeper, crosstie, design standard, holes, web opening, railway infrastructure, ductility, fragility, failure criteria.

1. INTRODUCTION

Globally, railway transportation has become one of the most essential and sustainable modes of transport, conveying cargoes, passengers, minerals, grains, and so forth. Over the past century, ballasted railway tracks have been heavily constructed as they offer cost-effective solutions to low to medium speed transportation (<250 km/h). Railway prestressed concrete sleepers (or called 'crossties') have been installed in the ballasted tracks for over 50 years (Remennikov and Kaewunruen, 2008). The railway sleepers are a main part of railway track structures. In general, the sleepers can be made of timber, concrete, steel or other engineered materials (Meesit and Kaewunruen, 2017). Prestressed concrete sleeper were initially introduced around many decades ago and at present are introduced in almost everywhere in the world. Their major roles are to distribute loads from the rail foot to the underlying ballast bed and to secure rail gauge under train traffics. Evidences from the fields revealed that railway track structures often experience high-intensity dynamic load conditions due to wheel/rail interactions associated with irregularities (Kaewunruen et al., 2017a; 2017b). In addition, railway track components are often being modified (by creating holes or web openings) at construction sites to fit with signaling gears, cables, ballises (train control equipment), and additional train derailment protections, such as guard rails, check rails, Earthquake protection rails, etc. The practical guideline for sleeper retrofit and repair has not been well established and many attempts were carried out based on trials and errors. Despite a common task in construction site, the failure mode and fragility of the concretes sleepers with holes and web openings have not been well documented in open literature. Thus, it is important to ensure that concrete crossties can be retrofitted and modified for add-on fixture in practice. The emphasis of this paper has been placed on the failure analysis and evaluation of the sleepers with holes and web openings. The insight into these premature damages has led to the proposal to introduce a new ductility index, in order to improve safety and reliability of railway infrastructure, and to enhance the structural safety of other concrete structures in railway built environment. The proposed ductility index has been correlated with structural failure modes observed in the laboratory and in the field and will help highlight the actual functionality of the sleepers in the field where they are embedded in ballast and unable to inspect by normal walking inspection practices.

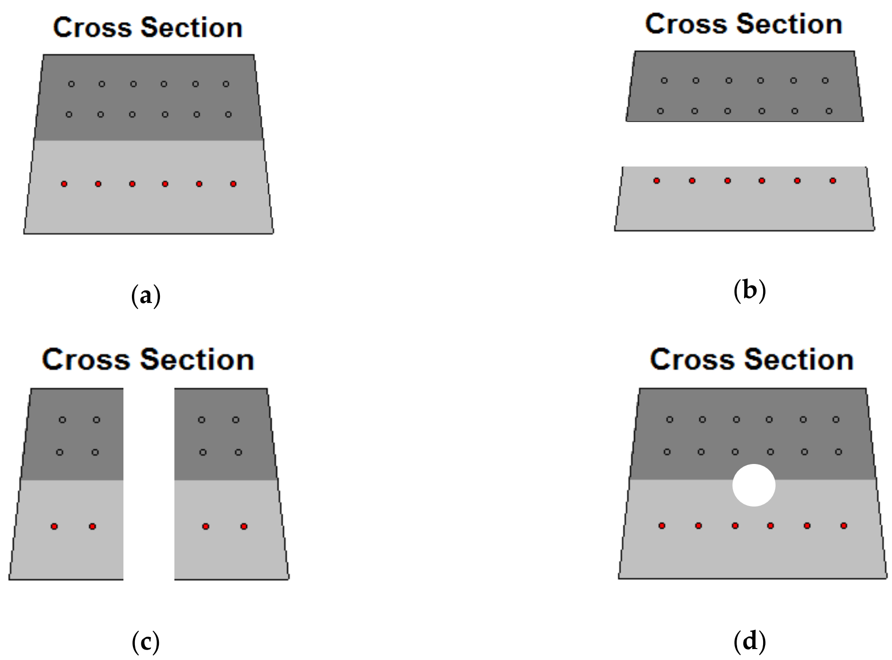
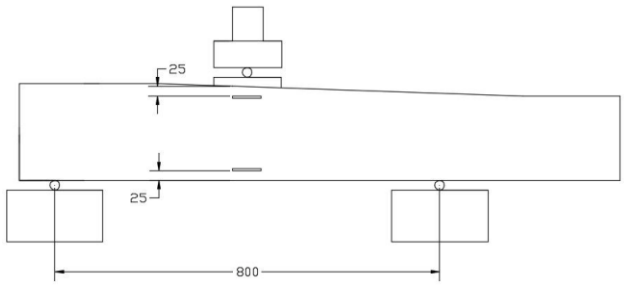


Figure 1. Web opening and holes in crossties in practice: (**a**) Full cross section of a traditional standard-gauge railway concrete crosstie; (**b**) Web Opening (or transverse hole); (**c**) Vertical hole; (**d**) Longitudinal or through hole (Gamage et al., 2017a; 2017b).

2. EXPERIMENTAL STUDY

The holes and web openings are generated using a high-speed diamond-coring machine on full-scale sleepers. Common types of holes and web openings in practice have been carried out including the vertical and longitudinal holes as well as the lateral through hole, as illustrated in Figure 1. These holes are often installed after construction to accommodate various needs such as cables, additional bolts, bracing system, lateral or third rail fixtures, etc. The position of the hole is often at the middle between the edge of rail and the sleeper end (with reduction to about the half of maximum shear force action). No steel reinforcement has been damaged from these holes and web opening. For practicality, 42mm diameter holes have been cored in a similar manner as in an actual construction. Then, they are tested under the prescribed static testing condition shown in Figure 2 in order to identify the comparable and repeatable residual energy toughness (Meesit et al., 2015; Meesit and Kaewunruen, 2017). Through the static tests, the load carrying capacity is plotted against railseat deflection. The fracture toughness can subsequently be identified by the integration (area under the curve) of load-deflection relationship (Kaewunruen and Remennikov, 2013; 2016). The comparative index is a ratio between the toughness with and without holes.



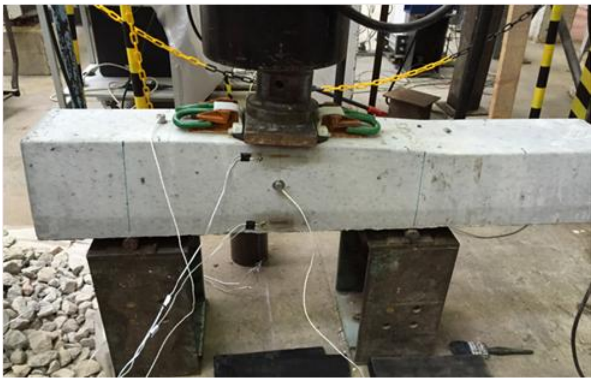


Figure 2. Standard type testing setup for performance benchmarking of sleeper capacity. Note that the type tests are normally used for quality assurance of materials and components.

In general, full load deflection curve can be found in Figure 3. The first stage of the curve is elastic stage when materials behave linearly in elastic range. Then, the nonlinear behavior takes place when the principal stress reaches the proportional yield stress and the materials make use of the nonlinear portion of the strength. Until the structural member reaches ultimate capacity or stability failure, the nonlinear portion dominates. At the ultimate point, the load deflection curve drops at certain extent due to the yielding of high strength strands and the spalling of concrete. The strength beyond this ultimate capacity, if the member is further loaded, is referred to as the residual fracture toughness in the post failure mechanism. The post failure mechanism can be clearly seen in Figure 3. It exhibits that the strands still provide the strength hardening effects to the residual load carrying capacity and the energy absorption mechanism until they reach the rupture capacity. The hardening effect is significant when more tendons remain and the effect decreases as the remaining number of tendons diminishes (Remennikov and Kaewunruen, 2014a; 2014b).

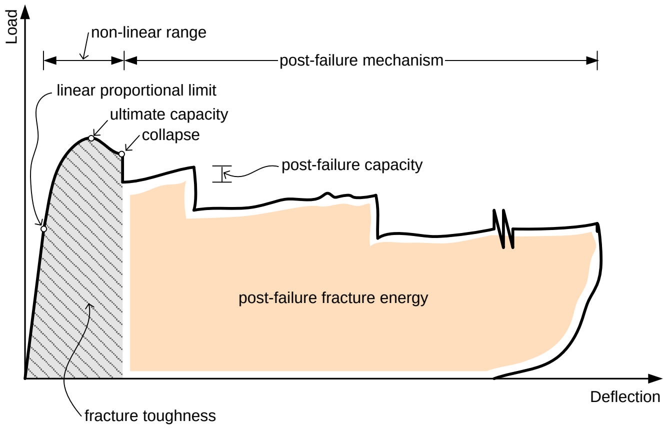


Figure 3. Schematic full load-deflection curve of structural member.

3. FRAGILITY AND FAILURE BEHAVIOUR

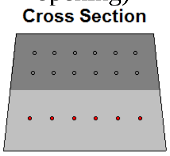
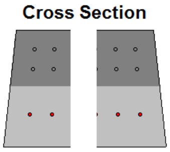
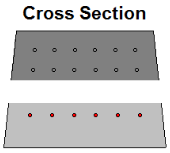
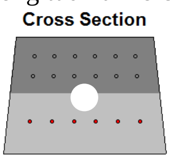
The static tests have been carried out in accordance with BS EN13230 (2009) for benchmarking purpose. The results reveal a very interesting behavior of the sleepers with holes and web openings. Table 1 shows the ultimate moment capacities of the crossties. The fragility and failure mode analysis has been evaluated from crack propagation. It is found that the sleepers with full cross-section and with a vertical hole exhibit a bending mode of failure. It is also found that there were some snaps of prestressing tendons (tendons reach their characteristic yielding stress) and the first bending cracks can be observed. The sleepers with longitudinal and transverse holes were failed by mixed shear and bending mode.

4. NEW DUCTILITY INDEX

Using load–deflection curves as illustrated in Figure 4, the ductility of the sleepers can be determined. Traditionally, the ductility index (based on displacement ratio) has been derived from the ratio of the maximum displacement over the first yield displacement of crossties (Δ_u/Δ_y). The first yield displacement, Δ_y, corresponds to the intersection of the tangents to the load displacement curve at the origin and ultimate displacement; and the maximum displacement represents the displacement at collapse state. Therefore, the use of the displacement ductility ratio presents a new criterion in addition to the strength criterion for predicting the early warning capability of railroad crossties. It is evident that holes and web openings generally undermine the maximum strength of concrete crossties. From Table 1, it can be observed that the first cracks developed in the crosstie without holes and those with vertical and longitudinal holes are bending cracks. It is important to note that the crossties failed in a bending related mode. In contrast, it is found that the sleeper with transverse holes failed in the shear mode, and diagonal cracks developed through the hole.

Figure 5 exhibits that the sleeper with transverse holes can failed suddenly at a brittle shear mode and yield the lowest ductility index. However, it is important to note that the concrete sleepers with vertical and transverse holes tend to have relatively lower ductility, resulting in less early warning of structural failure.

Table 1 Failure mode criteria of sleepers with hole and web opening

Crossties	Maximum moment capacity, kN.m	Failure mode
Intact (no holes or web opening) 	68 (100%) Bending failure	
With 42mm diameter vertical hole 	61 (90%) Bending failure	
With 42mm diameter transverse hole 	56 (82%) Mixed bending-shear failure	
With 42mm diameter longitudinal hole 	61 (90%) Mixed bending-shear failure	

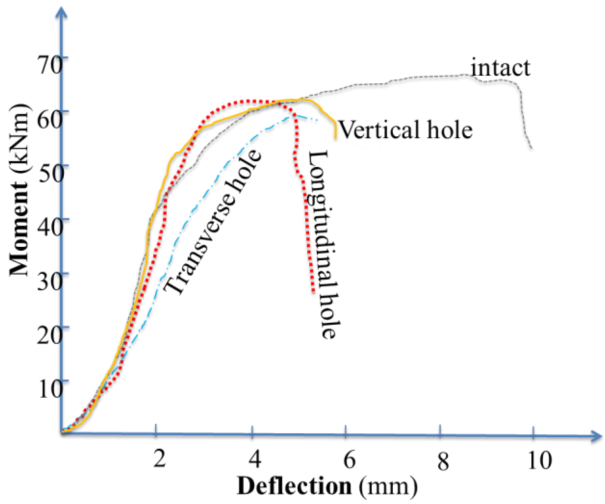


Figure 4. Schematic full load-deflection curve of railway concrete sleepers.

In reality, using traditional index can also mislead the functionality of the sleepers. The new ductility index has been derived from the ratio of ultimate displacement over the displacement at maximum moment (Δ_u/Δ_{max}). It is evident that holes and web opening generally undermine the maximum strength of concrete sleepers. It can be observed that the traditional ductility index can provide an unclear impression of structural condition of the sleepers. The traditional ductility could imply that the sleepers still have significant reserve capacity prior to their failures. In contrast, the new ductility index offers a better justification of structural health of the sleepers. Using maximum load (or failure load) to enable a new index will assure track engineers for what they can expect from the sleepers embedded in ballasted tracks. The rationale behind it is that the sleepers may crack but the track inspectors may not be able to observe the crack until the crack forms a crushing of concrete (at the maximum load). The severe damages on sleepers are generally detected when the cracks grow significantly.

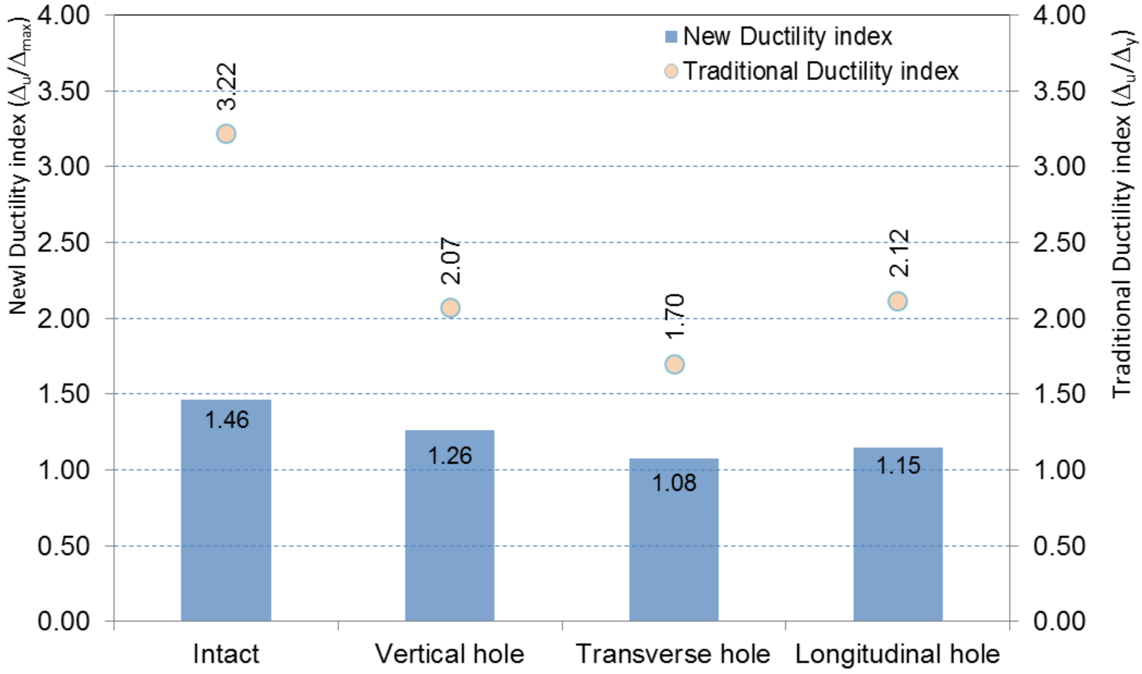


Figure 5. Ductility indices of railway concrete sleepers

5. CONCLUSION

The ductility of railway prestressed concrete sleepers is often undermined by the holes and web openings created to cater signaling gears or other functional purpose. It is important for track and rail engineers to assure that the structural health inspection of concrete sleepers on sites can be carried out in a proper manner. Note that existing codes of practice could not accurately estimate such aspects; and they could not portray unforeseen damage nor an early warning. By the comparative results obtained from these ductility indices, it is recommended that transverse and longitudinal holes should be particularly avoided. This is because the transverse and longitudinal holes can reduce the ductility of the sleepers and such the hole and web opening can also impair energy toughness and importantly ductility. The insight into structural behavior of the concrete sleepers with holes and web opening will enable safer built environment in railway corridor, especially for concrete sleepers whose structural inspection is very difficult in practice. Our field experience and experimental outcomes suggest that the new ductility index should be adopted for embedded sleepers where small cracks cannot be visually observed.

6. ACKNOWLEDGMENTS

The first author wishes to gratefully acknowledge Australian Academy of Sciences and the Japan Society for Promotion of Science (JSPS) for his JSPS Invitation Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the University of Tokyo, Tokyo, Japan. The JSPS financially supports this work as part of the research project, entitled "Smart and reliable railway infrastructure". The authors would also like to gratefully acknowledge the University of Birmingham's BRIDGE Grant, which financially supports this work as part of the project "Improving damping and dynamic resistance in concrete through micro- and nano-engineering for sustainable and environmental-friendly applications in railway and other civil construction". This project is part of a collaborative BRIDGE program between the University of Birmingham and the University of Illinois at Urbana Champaign. Special thanks to European Commission for H2020-MSCA-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network". In addition, the sponsorships and in-kind assistance from CEMEX, Network Rail, Rail Safety and Standard Board UK, are highly appreciated.

7. REFERENCES

British Standard, (2009) Railway applications. Track. Concrete sleepers and bearers. Prestressed monoblock sleepers: BSI. 32. London, U.K.

Gamage, E.K.; Kaewunruen, S.; Remennikov, A.M.; Ishida, T. (2017a) Toughness of Railroad Concrete Crossties with Holes and Web Openings. Infrastructures, 2, 3. doi:10.3390/infrastructures2010003

Gamage, E.K.; Kaewunruen, S.; Remennikov, A.M.; Ishida, T. (2017b) Reply to Comment on Toughness of Railroad Concrete Crossties with Holes and Web Openings. Infrastructures, 2, 5. doi:10.3390/infrastructures2010005

Kaewunruen, S., Meesit, R., (2016), Sensitivity of crumb rubber particle sizes on electrical resistance of rubberised concrete, Cogent Engineering, 3(1): 1126937. doi: 10.1080/23311916.2015.1126937

Kaewunruen S, Sussman JM and Matsumoto A., (2016), Grand Challenges in Transportation and Transit Systems. Front. Built Environ. 2:4. doi: 10.3389/fbuil.2016.00004

Kaewunruen, S. and Remennikov, A., (2006), "Nonlinear finite element modelling of railway prestressed concrete sleeper." 10th East Asia-Pacific Conference on Structural Engineering and Construction, Aug 3 - 5, Bangkok, Thailand, Vol. 4, 323-328.

Kaewunruen, S. and Remennikov, A.M., (2013), "On the residual energy toughness of prestressed concrete sleepers in railway track structures subjected to repeated impact loads." Electronic Journal of Structural Engineering, 13(1), 41-61 (invited).

Kaewunruen, S., Remennikov, A.M, (2016), "An overview of current state of practice in track vibration isolation," Australian Journal of Civil Engineering, 14(1): 63-71.

Kaewunruen, S, Singh, M, Akono, A-T & Ishida, T. (2017a), Sustainable and self-sensing concrete. in Proceedings of the 12th Annual Concrete Conference., MAT31, Cha Am, Thailand , pp. 1-10.

Kaewunruen, S., Meesit, R., Mondal, P., (2017b), Early-age dynamic moduli of crumbed rubber concrete for compliant railway structures, Journal of Sustainable Cement-Based Materials, in press

Kimani, S.K., Kaewunruen, S. (2017), Free vibrations of precast modular steel-concrete composite railway track slabs, Steel & Composite Structures, 24(1): 113-128.

Meesit, R., Kaewunruen, S., Mondal, P., (2015) Dynamic properties of early-age micro-and nano-engineered concrete for compliant railway structures, RILEM International Conference on Strategies for Sustainable Concrete, Rio de Janeiro, Brazil, December 14-16.

Meesit, R., Kaewunruen, S., (2017), Vibration characteristics of micro-engineered crumb rubber concrete for railway sleeper applications, Journal of Advanced Concrete Technology 15 (2), 55-66.

Remennikov, A.M. and Kaewunruen, S., (2008) "A review on loading conditions for railway track structures due to wheel and rail vertical interactions," Progress in Structural Engineering and Materials, incorporated in Structural Control and Health Monitoring, 15 (2), 207-234.

Remennikov, A.M., and Kaewunruen, S. (2014a), "Experimental load rating of aged prestressed concrete sleepers." Engineering Structures, 76(10): 147-162.

Remennikov, A.M., and Kaewunruen, S. (2014b), "Determination of remaining prestressing force in concrete sleepers using dynamic relaxation technique." ASCE J of Performance of Constructed Facilities, 29 (5), 04014134.

Sae Siew, J., Mirza, O. and Kaewunruen, S., (2015), "Nonlinear finite element modelling of railway turnout system considering bearer/sleeper-ballast interaction", Journal of Structures, doi: 10.1155/2015/598562

Sae Siew, J., Mirza, O. and Kaewunruen, S., (2016), "Torsional effect on railway track structures of turnout crossing impact", ASCE Journal of Transportation Engineering Part A Systems, in press.